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Original Article

A Chemical and Thermal Characterization Analysis of Coconut Shell Powder

Aditya Chaudhary [1], Rohit Srivastava [1], Pragya Srivastava [1], Anurag Shrivastava [1]

1. *Mechanical Engineering, S R Institute of Management and Technology, Lucknow, IND*

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Abstract

The chemical characterization of Coconut Shell Powder (CSP) is analyzed with thermogravimetric analysis (TGA) and Fourier Transform Infrared (FTIR). TGA was performed as part of the thermal characterization to provide an understanding of the thermal stability and thermal degradation of CSP. The TGA performed was conducted under nitrogen with a sample weight of 20 mg and the % weight loss was reported from 50 °C to 650 °C at 10 °C/min according to the ASTM E1131. The TGA revealed that CSP was thermally stable up to 150 °C with a small mass loss of about 6.097% corresponding to the initial loss of moisture and volatiles. The larger mass loss of 75.369% occurred between 156.07 °C and 655.37 °C due to the degradation of hemicellulose, cellulose, and lignin where the final residue was 18.291% indicating a high char yield and thermal stability. The FTIR analysis was performed on the CSP in the wavenumber range of 4000-500 cm^{-1} *Biomass Characterization* as per ASTM E1252 standard to determine important functional groups. The CSP displayed broad absorption bands defining O-H stretching (3297.73 cm^{-1}), C-H stretching (2918.39 cm^{-1}) and C=C stretching (1622.28 cm^{-1}) demonstrating oxyhydroxyl, aliphatic, and aromatic structures, respectively. The cellulose and hemicellulose structures corresponded to peaks located at 1424.289 cm^{-1}, 1253.354 cm^{-1}, and 1100.206 cm^{-1}. The peaks that were observed below 700 cm^{-1} correspond to functional groups which would be representative of both aromatic and inorganic compounds. In conclusion, the results of TGA and FTIR support the CSP's thermal stability and organic complexity, adding further weight to the case for the CSP as a value-added, sustainable material.

Categories: Advanced Manufacturing Technologies, Advanced Materials, Materials Engineering

Keywords: coconut shell powder (csp, thermogravimetric analysis (tga), fourier-transform infrared spectroscopy (ftir), thermal stability, functional group analysis, biomass characterization

Introduction

The coconut shell, a stony and fibrous part of the fruit of the coconut tree (*Cocos nucifera*), is a significant lignocellulosic agro-waste produced in copious volumes, especially in tropical climates such as India, Sri Lanka, the Philippines, and Indonesia [1,2]. The utilization of coconut shells, a by-product of the coconut processing industry's supply chain, has led to the coconut shell being seen as waste [3]. The coconut shell thus faces a waste disposal issue [4]. With a growing awareness and desire for biomass valorization, the coconut shell powder (CSP) has become a potentially valuable raw material for many scientific and industrial applications with environmental benefits, because CSP has global availability, chemical richness, mechanical capacity, and eco-friendly attributes [5,6].

Crushed, dried, and ground coconut shells are the sources of CSP. The resulting powder has a complex structure of cellulose, hemicellulose, and lignin [7]. These materials are organic polymers, which make up the whole plant biomass. The lignocellulosic nature gives CSP its beneficial characteristics - high carbon content, good thermal stability, low ash

yield, and strong adsorption potential [6-8]. This allows CSP to be used in several applications, including activated carbon, bio-composites, wastewater treatment, polymer reinforcement, and as a precursor for biofuels or pyrolyzed products [5,6-9].

The cellulose and hemicellulose components contribute significantly to CSP's mechanical and biodegradable properties [10,11]. Cellulose is a crystalline polysaccharide associated with strength and rigidity, while hemicellulose has amorphic properties and is a heteropolymer that affects thermal degradation properties in CSP. In contrast, lignin is an aromatic heat stable and hydrophobic dominant macromolecule, which gives CSP resistance to microbial attack, water absorption, and thermal breakdown. These three components together will ultimately be responsible for CSP's physicochemical behavior in thermal and chemical processing [11].

Thermal analysis techniques like Thermogravimetric Analysis (TGA) are significant in characterizing the stability and decomposition of CSP. At elevated temperatures under inert conditions (e.g. nitrogen atmosphere), CSP can usually be decomposed in a multi-step process that reflects the breakdown of its sequential structural polymers. In general, moisture will evaporate at temperatures below 150 °C, hemicellulose will start to degrade at around 200 °C, cellulose will degrade fairly rapidly near 300 °C, and lignin will account for continuous mass loss over a broad temperature range of 500-650 °C . This decomposition profile demonstrates CSP's predictable pyrolytic behavior, as it can be carbonized, gasified, or thermally processed.

Fourier Transform Infrared (FTIR) Spectroscopy can also be utilized to understand the functional groups and chemical bonds present in CSP. Specifically, FTIR spectra usually show O-H, C-H, C=O, and C-O-C vibrational bands that denote the presence of alcohols, phenols, ethers, aromatic rings, and glycosidic linkages. These groups will greatly enhance CSP's surface reactivity and compatibility with polymers and resins if the CSP is to be used as a composite. Furthermore, such functional groups will increase its ability to adhere to contaminant ions during an adsorption process, which make CSP an excellent medium for environmental remediation.

The sustainable and renewable characteristics of CSP further support its application in both green engineering and circular economy approaches [6]. The use of coconut shell waste provides value to agro-residues, while helping to mitigate both ecological pollution and the reliance on non-renewable resources. CSP-based materials offer the opportunity to develop biodegradable, low-cost, and carbon-rich materials in line with current developments in bio-based products [12,13].

In consideration of the above, the present study explores the chemical and thermal characterization of CSP using a variety of analytical methods, including TGA and FTIR. The characterization is intended to confirm the stages of decomposition, identify the major functional groups, and compare the chemical and thermal characterization with published literature. This work aims to validate the capacity of CSP for both thermochemical conversion and sustainable materials development.

A few previous investigations have documented the thermal degradation and chemical composition of CSP, supporting its characterization in energy, environment, and material science. In the work of Ngah et al., thermal degradation of CSP showed a typical three-phase degradation process in nitrogen: phase one was moisture loss (<150 °C), phase two was hemicellulose decomposition (200 to 250 °C) and phase three was lignin degradation (500 °C). The three phases conform closely with the results in the current paper, whereby the high mass loss (156.07 °C to 655.37 °C) supports the thermal stability of CSP and relative homogeneity in composition [14].

Liyanage and Pieris presented TGA findings indicating maximum cellulose degradation at around 338 °C and hemicellulose degradation starting at around 290 °C. Their analysis showed char residue between 16 and 25%, which compares well with the 18.291% mass residual in our analysis, suggesting CSP has a high fixed-carbon content and is useful as a solid for pyrolysis [15].

The FTIR study for this analysis is consistent with Andezai et al. and Kirby et al. who were able to identify broad O-H stretching bands near 3300 cm^{-1}, aromatic C=C peaks at around 1590 cm^{-1}, and strong C-O-C linkages between 1100 and 1020 cm^{-1}. These peaks confirmed the presence of cellulose, hemicellulose, and lignin in the coconut shell structure [14].

By comparison with Rout, the first two stages of pyrolysis would occur in the range of 250-500 °C with a significant amount of lignin oxidation, as has been reported [15].

Comparisons with the literature reinforce the reproducibility and consistency of CSP and its potential for future applications ranging from carbon materials, and polymer fillers to versatile and sustainable feedstocks based on its consistent, stable, and diverse functional groups. This represents excellent encouragement for further research and development regarding the application of CSP.

Recent studies (2022-2024) have explored the utilization of CSP in biochar production, polymer composite reinforcement, activated carbon development, and wastewater adsorption systems. These investigations demonstrate the increasing industrial interest in CSP as a sustainable and value-added biomass resource. However, consistent benchmarking of commercially available CSP under standardized ASTM protocols remains limited, which the present study aims to address.

Materials And Methods

For this study, CSP was used as the test case material. The CSP was purchased as pre-ground from a local market in Lucknow, Uttar Pradesh, India, so it would be easy for any reader to investigate, find out about, and trace the source for supply and assurance of quality. The powder was well pre-ground to a fine and uniform size, meaning that it did not require additional grinding or milling operations.

The CSP sample was first oven-dried at 80 °C for 24 hours to eliminate residual moisture prior to analysis. The powder was sieved to produce a particle size smaller than 150 µm. To prepare the sample for TGA and FTIR analyses, the powdered sample was ball-milled for 2 hours to achieve a homogeneous distribution of particles as per the ASTM E1629 method.

Before conducting any tests with the CSP, it was kept in a controlled environment to minimize the chance of atmospheric contamination or moisture uptake. Then the material was placed in an airtight container to secure its consistency and exclude any outside influences. A visual inspection of the powder was done to identify the presence of cleanliness, homogeneity, and consistency of the material, which would be suitable for further characterization even beyond what was tested in the study.

TGA was performed to observe the thermal degradation behavior of CSP under an inert atmosphere. The parameters used for TGA are presented in Table *1*. This analysis assisted in tracking the weight loss of hemicellulose, cellulose, and lignin with respect to temperature.

S. No	Parameter	Details
1	Material	Coconut Shell Powder (CSP)
2	Sample Preparation	Ball-milled after grinding
3	Sample Weight	20 mg
4	Heating Rate	10 °C per minute
5	Temperature Range	50 °C to 650 °C
6	Atmosphere	Nitrogen (N_2)
7	Gas Flow Rate	20 ml/min
8	Crucible Type	Platinum
9	Standard Followed	ASTM E1131

TABLE 1: Parameters used for TGA

TGA, Thermogravimetric Analysis

Fourier Transform Infrared (FTIR) Spectroscopy

FTIR was carried out to analyze the functional groups and molecular structure of CSP (cellulose, lignin, starch, protein). The parameters employed in the FTIR analysis are provided in Table *2*. This analysis allowed for the identification of characteristic vibrational transitions associated with lignocellulosic materials.

S. No.	Parameter	Details
1	Wavenumber Range	4000 cm^{-1} to 500 cm^{-1}
2	Spectral Resolution	4 cm^{-1}
3	Number of Scans	32–64
4	Environment	Room temperature, dry conditions
5	Standard Followed	ASTM E1252

TABLE 2: Parameters used for FTIR

FTIR, Fourier Transform Infrared

Results And Discussion

TGA of CSP

TGA of CSP was performed in a nitrogen environment, and the TGA showed the typical multi-stage degradation behavior in lignocellulosic biomass (as shown in Figure *1*). As the CSP temperature increased from 50°C to 650°C at 10°C/min, there were three distinct ranges of mass loss corresponding to the thermal degradation of the main molecular components, hemicellulose, cellulose, and lignin.

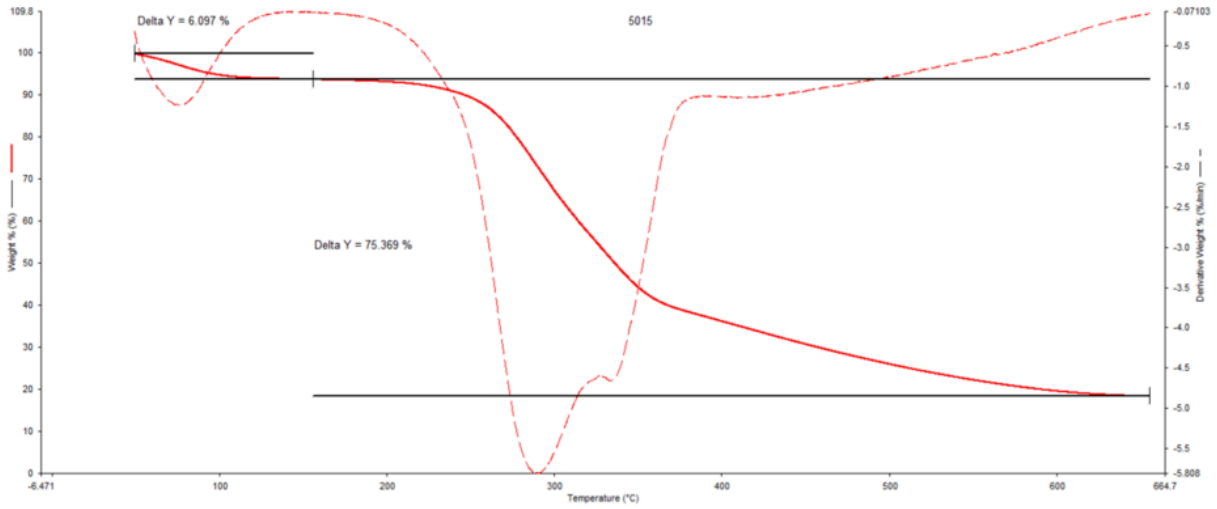

FIGURE 1: Thermogravimetric Analysis (TGA) graph of Coconut Shell Powder

Because of CSP's thermal stability up to about 150°C, it only experienced a slight mass loss of 6.097%, that can be attributed to physically adsorbed water and volatile organic compound evaporation, as well as the absence of significant chemical degradation, demonstrating an ability to withstand thermal degradation under moderate levels of thermal exposure.

After approximately 150°C, the major degradation zone, which was seen between 156.07°C and 655.37°C, where the sample experienced a large mass loss of 75.369%, showed that hemicellulose, cellulose, and lignin underwent a sequential thermal degradation phase.

The shoulder of the thermogram at around 200°C indicates the initial decomposition of hemicellulose. Hemicellulose is a low molecular weight branched biopolymer, so it decomposes at a lower temperature than the more crystalline and thermally stable carbohydrate polymer cellulose. The sharp peak at approximately 300°C represents the rapid degradation of cellulose. Furthermore, the gradual negative slope from 350°C to 500°C indicates the slow degradation of lignin, a complex aromatic macromolecule known to have a wide range of degradation temperatures.

At the conclusion of the active decomposition phase, the final mass of the sample residue at 650°C was 18.291%. As expected, this residue is a combination of char and inorganic ash, indicating that there is a fair amount of fixed carbon (char) and structural material (inorganic ash) remaining. Under pyrolysis conditions of high temperature and high char yields, predictions can be made about the char yield.

Data from the TGA test are recorded in Table *3*, highlighting the relative thermal transitions and mass losses.

S. No.	Temperature Range (°C)	Observed Mass Loss (%)	Interpretation
1	50–150	6.097	Loss of moisture and low-boiling volatiles
2	156.07–655.37	75.369	Decomposition of hemicellulose, cellulose, lignin
3	Residual Mass at 650 °C	18.291	Char and ash (thermally stable residue)

TABLE 3: Thermogravimetric data summary for Coconut Shell Powder and thermogram exhibited a three-stage thermal degradation pattern

Stage I (Drying Phase): The process began at 50 °C, that is, it was happening in a range between 50 °C and 150 °C, and the weight primarily consisted of moisture loss. The absence of any distinct inflections or peaks in that range demonstrated that there was no substantial degradation of structure occurring in this process.

Stage II (Active Pyrolysis): The process began after 150 °C, where thermal degradation of structural biopolymers commenced (most notably in hemicellulose, which initiates around 180-220 °C, which is supported by the small shoulder in the weight loss curve), and cellulose was rapidly decomposing (there was a clear rate of change in moisture loss), with a sharp inflection occurring soon after, at approximately 300 °C (between 280 and 350 °C). Lignin, having a wider range of mass loss that was less sharp (over a longer range between typically 200 and 500 °C), indicated slower decomposition and showed a degree of thermal stability against decomposition.

Stage III (Residual Formation): The last observed weight plateau occurring above 655 °C is interpreted to be residual inorganic/carbonaceous content. The inherent char yield of 18.291% indicates that stable compounds were produced.

• A small peak near 200 °C (hemicellulose),

• A large peak near 300 °C (cellulose),

• A broad shoulder (lignin) until about 500 °C,

confirming the multi-phase degradation behavior shown in the main TGA curve.

These findings are conclusive in demonstrating CSP's makeup and how it transforms under heat. The thermal transitions shown correspond with literature in understanding the thermal behavior of lignocellulosic materials. Inconsistencies in the separate decomposition zones, high char residue, and the unclear nature of CSP's thermoplastic behavior may highlight applications in thermally demanding environments where thermal resistance and carbon retention are desirable. Furthermore, the lack of strong exothermic reactions or combustion spikes confirms that purging with inert nitrogen gas and maintaining an inert atmosphere is indeed effective and allows for experimentation of CSP's pyrolytic performance without oxidative influences. Therefore, this leads to the evaluation of CSP's pyrolytic performance. The consistency in the different mass loss stages firmly solidifies the homogeneity of the sample and the consistency of the analysis.

In conclusion, the TGA findings support the argument that CSP is capable of a predictable thermal behavior, demarcating temperature zones corresponding to organic constituents, at least thermally stable residue for thermal stability and charring applications, that supports investigation into CSP for thermochemical applications in particular, where

considerations for stability, predictable decomposition behavior, and charring offer another layer of performance consideration.

The TGA of CSP in the present study exhibited strong consistency with prior work. Ngah et al. documented the first moisture loss occurring below 150 °C and major degradation of hemicellulose between 200-350 °C, and lignin degraded up to 500 °C. The overall decomposition, as reported here aligned with the range of ~156.07 °C to 655.37 °C with immediate residue observed [14].

Likewise, Liyanage and Pieris reported peak degradation temperatures of hemicellulose and cellulose around 290 °C and 338 °C, respectively. There was an onset of cellulose loss at ~300 °C in the results above, and the final residue (16-25%) was comparable to the char yield of 18.291% determined in this study [15].

Rout described a two-stage pyrolysis between 250 and 500 °C with char yields up to 35%, which is consistent with the fixed carbon being present as reported in the residual mass [15].

In addition, Andezai et al. and Kirby et al. confirmed the gradual degradation of lignin in CSP up to 900 °C, and the significant amount of thermal resistance also validated our finding of a stable, multi-phase decomposition process with a negligible amount of early-stage weight loss [14].

In summary, the comparisons provide evidence of the reproducibility, reliability, and lignocellulosic thermal behavior of CSP across studies.

FTIR characterization overview of CSP

FTIR spectroscopy characterization was included as part of the chemical characterization of CSP, a lignocellulosic biomass consisting primarily of cellulose, hemicellulose, and lignin. The FTIR test was carried out according to ASTM E1252, covering the CSP in the wavenumber range of 4000-5000 cm^{-1} to determine functional groups and explore the organic complexity, reactivity, and sustainability potential of CSP.

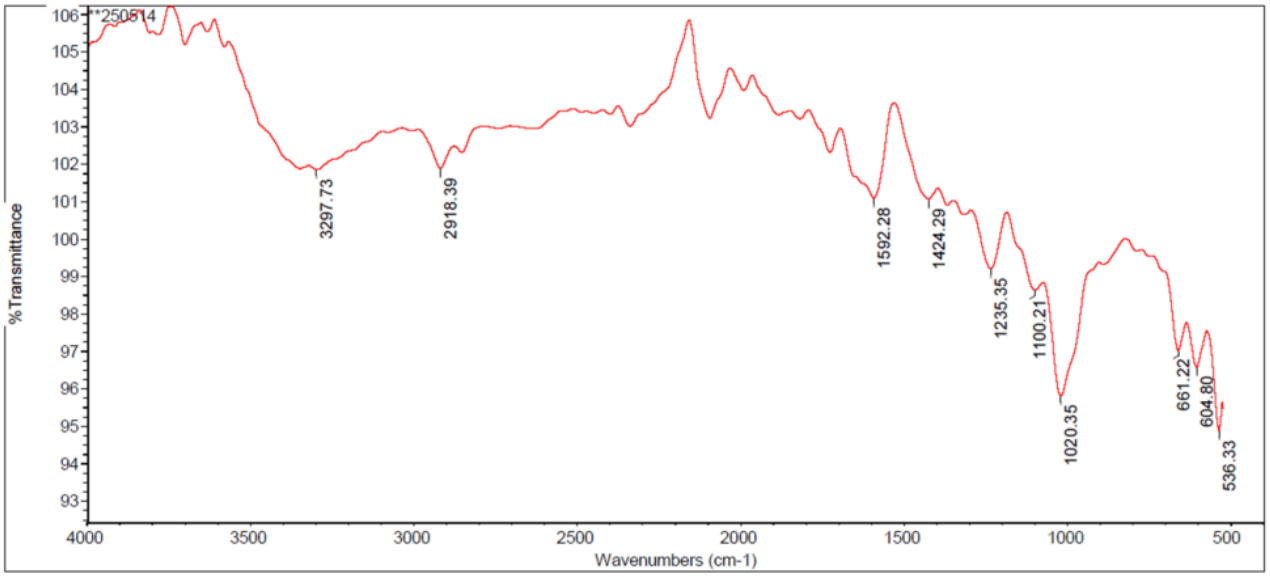

FIGURE 2: FTIR spectrum of Coconut Shell Powder showing key functional groups

FTIR, Fourier Transform Infrared

The FTIR spectrum of CSP is shown in Figure *2*, and consists of multiple absorption peaks that reflect the presence of specific chemical bonds and functional groups. A strong broad absorption band at 3297.73 cm^{-1} corresponds to O-H stretching vibrations and these types of -OH groups are usually present in alcohols and phenolic compounds. The

presence of -OH groups improves the hydrophilic property of the CSP, which is important for adsorption as well as for reactivity through carbonization under thermal or chemical experimental conditions.

The absorption at 2918.39 cm^{-1} reflects aliphatic C-H stretching from $-CH_2$ and $-CH_3$ groups, which are characteristic of fatty acids and lignin. Again, these aliphatic compounds provide information on the potential thermal degradation pathway and combustion characteristics of CSP, making it a candidate for bio-filler or bio-fuel precursor.

The peak at 1592.28 cm^{-1} can be assigned to aromatic C=C stretching, supporting the presence of aromatic rings resulting from lignin. Lignin is an important structural polymer in CSP that contributes to its rigidity and thermal stability, while also providing mechanical reinforcement in composites. A band at 1424.29 cm^{-1} is associated with C-H bending vibrations (of aromatic systems), further supporting structural diversity and a polymeric nature that is typical for lignin derivatives.

At 1235.35 cm^{-1}, an important peak assigned to C-O stretching vibrations of aryl ethers and phenolic groups supports an important structural group associated with CSP and also suggests cross-linking that follows during thermal or chemical modification, as well as CSP's potential for surface functionalization. A peak associated with C-O-C stretching vibrations appears at 1100.21 cm^{-1}. The C-O-C stretching vibrations that are representative of cellulose and hemicellulose feature glycosidic linkages which imply a polysaccharide backbone structure, and therefore increased biodegradability of the CSP.

The 1020.35 cm^{-1} peak derives from C-O stretching vibrations of primary alcohols and carbohydrates that contribute to increased water affinity of CSP, thus enabling CSP to be employed as a filtration and adsorption material. In the lower frequency region, the peaks at 661.22, 604.80, and 536.33 cm^{-1} are attributed to the skeletal ring deformation and out-of-plane bending motions of aromatic structures, as well as any residual inorganic or mineral components.

In summary, FTIR analysis provides evidence of the hydroxyl, aliphatic, aromatic, ether, and alcohol functional groups, suggesting that CSP does indeed have considerable chemical diversity and usefulness in biocomposites, adsorption systems, and biofuels. Coupled with the TGA data, the results presented here give a more complete picture of the chemical composition and thermal characteristics of CSP, which will support a viable sustainable and eco-friendly material.

The peak positions in the FTIR spectrum of CSP present an overview that is unsurprisingly consistent with the literature. The O-H stretching at 3297.73 cm^{-1} that corresponded to the hydroxyl groups associated with cellulose and hemicellulose was close to the values reported by Andezai et al. and Liyanage and Pieris, who observed peaks near 3325–3400 cm^{-1}. Furthermore, we observed a C-H stretching peak at 2918.39 cm^{-1} in CSP which corresponds to aliphatic chains from lignin and fatty acids that align with previously reported literature values for this stretching band around 2925 cm^{-1} [14,15].

There was a C=O peak at 1735 cm^{-1} in the results of Andezai et al.; however, it was only present faintly in our CSP due to either spectroscopic overlap or low amounts of acetylated hemicellulose. The peaks at 1592.28 cm^{-1} and 1424.29 cm^{-1} are indicative of aromatic skeletal vibrations in the range of 1512-1449 cm^{-1}, further confirming the presence of lignin [14].

Finally, the observed C-O-C and C-O stretching bands in the range of 1020-1150 cm^{-1} were consistent with the literature on ether and polysaccharide structures, which further corroborate CSP's lignocellulosic nature and provide additional evidence for its development as a bio-based reinforcing filler within polymer composite materials.

Thermogravimetric and FTIR analysis of biomass

TGA of the sample indicated three primary stages of thermal decomposition. The first stage, between 50 and 150 °C, exhibited a loss in mass of 6.10%, indicative of evaporation of moisture and light volatile compounds. The second stage, between 156.07 and 655.37 °C, indicated the bulk mass loss of 75.37%, which is suggestive of the multistage pyrolysis of lignocellulosic materials. Characteristic DTG maxima at around 200 °C, 300 °C, and between 350 and 500 °C are related to hemicellulose decomposition, cellulose decomposition, and lignin decomposition, respectively. The last one at temperatures above 650 °C resulted in a residue of 18.29%, which is due to the formation of carbonaceous char and ash. FTIR analysis further established the chemical composition of the sample. Broad and intense absorption at 3297.73 cm^{-1}

confirmed the presence of hydroxyl groups in lignin, hemicellulose, and cellulose; medium peaks at 2918.39 cm^{-1} and 1592.28 cm^{-1} were assigned to aliphatic C-H stretching and vibrations of aromatic C=C in the lignin backbone. The weak peak at 1735 cm^{-1} was indicative of trace acetylated hemicellulose. Other strong peaks at 1235.35 cm^{-1} and 1100.21 cm^{-1} reconfirmed aryl ether/phenolic groups and glycosidic linkages in lignin, cellulose, and hemicellulose. The other bands noticed at 1424.29, 1020.35, 661.22, 604.80, and 536.33 cm^{-1} corresponded to C-H bending, aliphatic primary alcohols, aromatic skeletal deformations, and trace inorganic residues, collectively asserting the lignocellulosic composition of the biomass.

In this paper, proximate and ultimate analyses were not conducted; however, based on literature data, the CSP has a volatile matter content ranging from 70 to 80%, a fixed carbon content of 15-25%, and an ash content that is very low (<5%). The chemistries of these filler materials are similar to those of other natural fillers, such as rice hulls and sawdust. In future work, we will perform more thorough elemental analyses to provide additional evidence for application-based validation.

Conclusions

The current study presents a complete thermal characterization of CSP utilizing TGA and FTIR spectroscopy, demonstrating the ability of CSP to be used as a lignocellulosic material for renewable thermochemical and industrial applications. The TGA profiles confirmed that CSP exhibited a multi-level thermal degradation pattern, with moisture loss <150 °C, loss of hemicellulose and cellulose observed at 200-350 °C, and a gradual decomposition of lignin occurring up to 655 °C, making it suitable for higher energy applications that require elevated temperatures. A significant residual mass (18.291%) indicates that CSP contains a considerable portion of fixed carbon, making it feasible for pyrolysis, carbonization, and energy recovery.

The FTIR analysis corroborated that the polysaccharide capabilities of CSP also included functionality comprising hydroxyl (O-H), aliphatic (C-H), aromatic (C=C), and ether (C-O-C) linkages, which are representative of cellulose, hemicellulose, and lignin. These functional groups enable a range of reactivity and thermal stability compatible with polymer matrices, creating applications that may be suitable for bio-composites, adsorbents, and environmentally friendly materials.

The strong experimental results aligned with the literature confirm reliability, reproducibility, and performance behavior of CSP's thermal and chemical characteristics. Overall, the findings suggest that CSP offers a promising, renewable, inexpensive, and biodegradable material that has high-value potential in energy, environmental, and material sciences.

Appendices

Appendix A - CIPET Test Report: Coconut Shell Powder (CSP) Characterization

This appendix compiles the official laboratory reports issued by the Central Institute of Petrochemicals Engineering & Technology (CIPET) for the characterization of CSP:

1. Report No. 0150 (Lucknow): Thermogravimetric Analysis (TGA)

2. Report No. 0154 (Raipur): Fourier-Transform Infrared Spectroscopy (FTIR)

The data presented here provide detailed evidence on the thermal degradation profile and functional group assignments of CSP. The appendix is structured in three parts for clarity:

Part A - Sample Particulars

Part A gives the information of the CSP sample utilized in the study. These are preparation, weight, appearance, packaging, condition on receipt, and storage prior to test.

The information is listed in Table *4*: Part A - Sample Particulars below.

Part B - Supplementary Information

Part B - Additional Information

Part B details the supporting information to test, such as the standards used, equipment utilized, heating rate, FTIR scan setup, and other notes.

The data are summarized in Table 5: Part B - Supplementary Information below.

Part C - Experimental Test Results

Part C discloses the experimental characterization data of CSP under TGA and FTIR. Findings are tabulated in the following tables:

Table 6: Part C1 - TGA Parameters: Enumerates the major experimental conditions applied during the TGA of CSP.

Table 7: Part C2 - TGA Weight Loss Stages: Illustrates the thermal degradation stages of CSP, such as moisture evaporation, polymer degradation, and residue formation.

S. No	Parameter	Details
1	Sample Name	Coconut Shell Powder (CSP)
2	Grade/Type/Class/Size	Not specified
3	Sample Preparation	Ball-milled after grinding
4	Sample Weight	~20 mg (for TGA)
5	Physical Appearance	Fine brown powder
6	Packaging Details	Moisture-protected airtight container
7	Condition at Receipt	Free-flowing, no agglomeration
8	Storage Before Testing	Desiccator at ambient temperature
9	Laboratory Reference	CIPET (Lucknow & Raipur) – Material Testing Divisions

TABLE 4: Part A – sample particulars

TGA, Thermogravimetric Analysis; CIPET, Central Institute of Petrochemicals Engineering & Technology

S. No	Parameter	Details
1	Standards Followed	TGA: ASTM E1131 FTIR: ASTM E1252
2	Instruments Used	TGA: TA Instruments (Platinum crucible, N_2 purge 20 ml/min) FTIR: DTGS detector, KBr pellet method
3	Heating Rate (TGA)	10 °C/min (50–650 °C range)
4	FTIR Scan Configuration	Range: 4000–500 cm^{-1}; Resolution: 4 cm^{-1}; Scans: 32–64
5	Deviations Reported	None
6	Supporting Documents	(i) TGA thermogram (ii) FTIR spectral plot
7	Sample Retention Policy	Retained for 3 months post-report, then disposed as per SOP

TABLE 5: Part B – supplementary information

TGA, Thermogravimetric Analysis; FTIR, Fourier-Transform Infrared Spectroscopy

Part C - Experimental Test Results

1. Thermogravimetric Analysis (TGA)

S. No	Parameter	Details
1	Temperature Range	50-650 °C
2	Atmosphere	Nitrogen (N_2)
3	Crucible Type	Platinum
4	Standard Method	ASTM E1131

TABLE 6: Table C1 - TGA parameters

TGA, Thermogravimetric Analysis

Stage	Temp. Range (°C)	Mass Loss (%)	DTG Peak/Shoulder (°C)	Interpretation
I (Drying)	50–150	6.097	None (gradual)	Removal of moisture and light volatiles
II (Pyrolysis)	156.07–655.37	75.369	~200 (hemicellulose), ~300 (cellulose), 350–500 (lignin)	Multistage decomposition of lignocellulosic components
III (Residual)	>650	18.291 (residue)	None	Formation of carbonaceous char and ash

TABLE 7: Table C2 - TGA weight loss stages

TGA, Thermogravimetric Analysis

Observations:

1. Total weight loss: 81.466%; residue: 18.291%, consistent with char yields (16-25%) reported in literature.

2. Distinct DTG shoulders: hemicellulose (~200 °C), cellulose (~300 °C), lignin (350-500 °C).

3. No oxidative peaks observed, confirming the inert nitrogen atmosphere.

4. Results are in strong agreement with earlier studies (Ngah et al.; Rout; Liyanage and Pieris).

Fourier-Transform Infrared Spectroscopy (FTIR)

Part C describes experimental characterization data of CSP, with emphasis on TGA and FTIR. The findings are outlined in the following tables:

Table *8*: FTIR Parameters: Includes the main experimental conditions applied to FTIR analysis of CSP, including wavenumber range, resolution, and sample conditions.

Table *9*: Stages of TGA Weight Loss: Displays the thermal degradation behavior of CSP with stages for moisture evaporation, polymer degradation, and residual mass formation.

S. No	Parameter	Details
1	Wavenumber Range	4000-500 cm^{-1}
2	Spectral Resolution	4 cm^{-1}
3	Number of Scans	32–64
4	Environment	Room temperature, dry
5	Standard Method	ASTM E1252

TABLE 8: Table C3 - Parameters for FTIR

FTIR, Fourier-Transform Infrared Spectroscopy

2. Fourier-Transform Infrared Spectroscopy (FTIR)

Wavenumber (cm^{-1})	Functional Group/Vibration	Intensity	Interpretation
3297.73	O–H stretching	Strong, broad	Hydroxyl groups in cellulose, hemicellulose, lignin
2918.39	C–H stretching	Medium	Aliphatic $–CH_2/–CH_3$ groups
1735 (faint)	C=O stretching	Weak	Trace acetylated hemicellulose
1592.28	C=C stretching	Medium	Aromatic rings (lignin backbone)
1424.29	C–H bending (aromatic)	Medium	Confirms aromatic skeletal vibrations
1235.35	C–O stretching	Strong	Aryl ethers/phenolics in lignin
1100.21	C–O–C stretching	Strong	Glycosidic linkages in cellulose & hemicellulose
1020.35	C–O stretching	Medium	Primary alcohols/carbohydrates
661.22, 604.80, 536.33	Skeletal deformations	Weak	Aromatic ring out-of-plane vibrations; minor inorganic residues

TABLE 9: Table C4 - Key FTIR absorption bands

FTIR, Fourier-Transform Infrared Spectroscopy

Additional Notes:

1. Spectrum displays a typical lignocellulosic fingerprint.

2. Weak C=O peak (1735 cm^{-1}) = low hemicellulose acetylation.

3. Strong polysaccharide signals in the 1020-1150 cm^{-1} region.

4. Results consistent with previous findings (Andezai et al., Kirby et al.).

Concluding Remarks

1. TGA data: Confirms a clear multiphase degradation with significant fixed-carbon residue.

2. FTIR data: Highlights diverse functional groups, validating CSP's lignocellulosic nature.

3. Overall outcome: CSP is demonstrated to be a promising, sustainable raw material for pyrolysis, composite reinforcement, and adsorption-based applications.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Aditya Chaudhary, Anurag Shrivastava, Pragya Srivastava

Acquisition, analysis, or interpretation of data: Aditya Chaudhary, Rohit Srivastava, Pragya Srivastava

Drafting of the manuscript: Aditya Chaudhary, Rohit Srivastava, Anurag Shrivastava, Pragya Srivastava

Critical review of the manuscript for important intellectual content: Aditya Chaudhary, Rohit Srivastava, Anurag Shrivastava

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